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Long-term variability in Saharan dust transport and its link to North Atlantic sea surface temperature

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[1] An understanding of the atmospheric distribution of Saharan dust is crucial for understanding many Earth-system processes. We demonstrate here a model simulation indicating that the August-September dust amount in the Tropical Atlantic is linked to the basin-wide North Atlantic sea surface temperature (SST). The increasing SSTs from 1979 to 2005 are associated with a strengthening cyclonic anomaly at 700 hPa in the tropical East Atlantic, reducing Saharan dust outflow into the Tropical Atlantic at latitudes between 10°–20°N. A decreasing dust amount over the same region is also observed by the Advanced Very High Resolution Radiometer. Given the previously observed anti-correlation between dust and tropical cyclone (TC) activity, the long-term variation of North Atlantic SST can then directly influence TC activity by changing a TC's maximum potential intensity and indirectly by modulating the transport of the dust-laden Saharan Air Layer. **Citation:** Wong, S., A. E. Dessler, N. M. Mahowald, P. R. Colarco, and A. da Silva (2008), Long-term variability in Saharan dust transport and its link to North Atlantic sea surface temperature, *Geophys. Res. Lett.*, *35*, L07812, doi:10.1029/2007GL032297.

1. Introduction

[2] The increase in Atlantic TC intensity over the past two decades has been linked to the change in sea surface temperature (SST) [*Emanuel*, 2005; *Goldenberg et al.*, 2001; *Hoyos et al.*, 2006; *Webster et al.*, 2005]. In addition, an anti-correlation between long-term time series of tropical cyclone frequency and the retrieved dust amount from the Advanced Very High Resolution Radiometer (AVHRR) over the Tropical Atlantic has been observed [*Evan et al.*, 2006a]. Although the detailed mechanisms linking dust amount to TC activity are still unknown, there is considerable evidence showing the suppression of tropical cyclone development [*Dunion and Velden*, 2004] by the dry and dust-laden Saharan Air Layer [*Carlson and Prospero*, 1972; *Karyampudi and Carlson*, 1988].

[3] One important question in studying the link between dust and TC activity is whether the SST and the amount of dust are completely independent. Previous studies have shown the importance of dynamical transport in determining the downwind distribution of dust [*Colarco et al.*, 2003; *Jones et al.*, 2004; *Mahoward et al.*, 2003; *Tegen and Miller*, 1998]. Using both satellite and model data, *Wong et al.* [2006] further showed that the direction of the cross-Atlantic transport of Saharan dust is related to the migration of an 850-hPa warm temperature anomaly. Here, we hypothesize that the lower tropospheric circulation is linked by variations in North Atlantic SSTs. In this way, SSTs can indirectly influence Saharan dust transport into the Tropical Atlantic.

[4] The goal of this paper is to investigate long-term variability in dust transport over the Tropical Atlantic during August and September, two prime months for hurricane formation, and to link this variability to the long-term change in North Atlantic SSTs.

2. Model Simulations and Data Analysis

[5] We utilized the Model of Atmospheric Transport and Chemistry (MATCH), which employs National Center Environmental Prediction (NCEP) reanalysis meteorological fields (T62 resolution, $\sim 1.8° \times 1.8°$, and 28 vertical levels) [*Mahoward et al.*, 2003, 2002; *Rasch et al.*, 1997], to study the long-term variation of Saharan dust amount over the Tropical Atlantic in 15°–60°W and 10°–20°N from 1979 to 2005. The region being studied is referred to as the "main development region" (MDR), where the formation of TCs frequently occurs [*Goldenberg et al.*, 2001; *Evan et al.*, 2006a]. The interannual variability of the MATCH monthly mean aerosol optical thickness (AOT) has been validated with a variety of observations. The variation of the monthly mean dust content has significant correlations with ground-based observations (of dust concentrations) over coastal sites around the Tropical Atlantic (e.g., Barbados, Bermuda, and Miami) and with available satellite observations (e.g., monthly mean aerosol optical depths from the Total Ozone Mapping Spectrometer and AVHRR) in the Tropics [*Mahowald et al.*, 2003]. We analyze the interannual variability of the averaged AOT for August-September, when tropical cyclones most frequently occur over the tropical North Atlantic.

[6] North Atlantic SSTs undergo a clear multi-decadal oscillation [*Delworth and Mann*, 2000; *Enfield et al.*, 2001; *Kerr*, 2000]; however, a warming trend since mid-1970s can also be clearly observed [*Mann and Emanuel*, 2006; *Santer et al.*, 2006; *Trenberth and Shea*, 2006]. To study the responses of atmospheric circulation and Saharan dust transport to trends in SST (1979–2005), we look for trend signals in lower tropospheric temperatures and modeled dust amount by applying rotated principal component analysis (PCA) [*Wilks*, 1995]. The rotation is performed to those trend-bearing principal components (PCs), which

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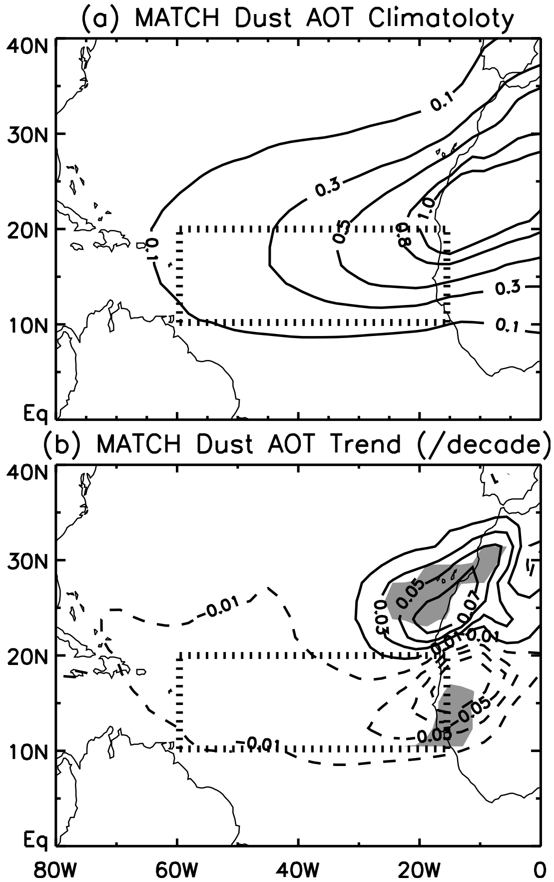

Figure 1. (a) Climatology of the MATCH August-September dust aerosol optical thickness (AOT) at 0.55 μm for the period 1979–2005. The contour levels are 0.1, 0.3, 0.5, 0.8, and 1. (b) Trends of the MATCH August–September dust AOT (/decade) for the period 1979–2005. The shaded area has trends that are non-zero at the 99% confidence level estimated by the F-test, and the thin dotted-line illustrates the tropical cyclone main development region. The contour levels are ±0.01, ±0.03, ±0.05, and ±0.07. The contours of positive values are in solid lines, and the contours of negative values are in dashed lines.

have non-zero linear trends at 2-σ level (σ is the error estimated for the trend), in order to obtain a single principal component that contains the maximized trend value. This analysis method helps us to identify the teleconnection pattern that has a long-term trend embedded in the year-to-year variation. The spatial distribution of the trends can then be estimated (for details please refer to auxiliary material[1]). The statistical significance of the trends is evaluated by F-tests for time series at each grid. We will also compare our lower tropospheric temperature variability in the tropics with the long-term variation in North Atlantic SST, as represented by the averaged Kaplan SST dataset [*Kaplan et al.*, 1998] over the Atlantic Ocean between 0°–70°N and 15°–60°W (hereafter simply referred to as the SST). We find that the SST variation described in our study is a basin-wide characteristic, independent of what region over the Atlantic Ocean is chosen for the analysis (i.e., it exists in both the MDR and higher latitudes).

[7] To evaluate the model simulation of long-term trend of dust amount in the MDR, we turn to the AVHRR dust dataset [*Evan et al.*, 2006b]. The AVHRR dust dataset contains the fractional coverage of heavy dust events (aerosol optical thickness at 0.63 μm > 0.6) in grid cells with 0.5° × 0.5° resolution [*Evan et al.*, 2006a, 2006b]. The data is averaged over the MDR (15°–60°W, 10°–20°N) for each month in 1982–2007, which is referred to as the AVHRR dust index. In this study we analyze this dust index for August and September from 1982 to 2005. Since the MATCH simulation does not include episodic events such as volcano eruptions, which can cause short-term variability in the AVHRR dust data, the AVHRR and the model time series are smoothed with a 5-year running mean to filter out short-term variations.

3. Results

[8] The average of the MATCH August-September dust AOT at 0.55 μm (since most satellite data report AOT at a visible wavelength) for the period 1979–2005 is shown in Figure 1a. The model shows that Saharan dust AOT peaks over the west coast of Africa, and the dust is blown into the tropical North Atlantic along 10–30°N and over the MDR.

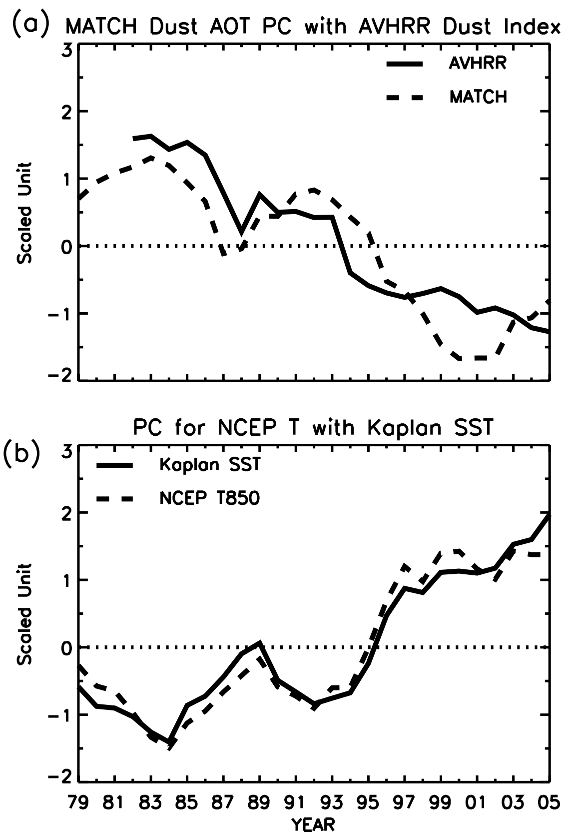

Figure 2. (a) Five-year running mean of the PC time series associated with the dust AOT trends in MATCH (dashed) compared with the AVHRR dust index (solid) over the tropical cyclone main development region. (b) The PC time series associated with the NCEP temperature trends at 850 hPa (dashed) compared with the averaged Kaplan North Atlantic SST (solid).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GL032297.

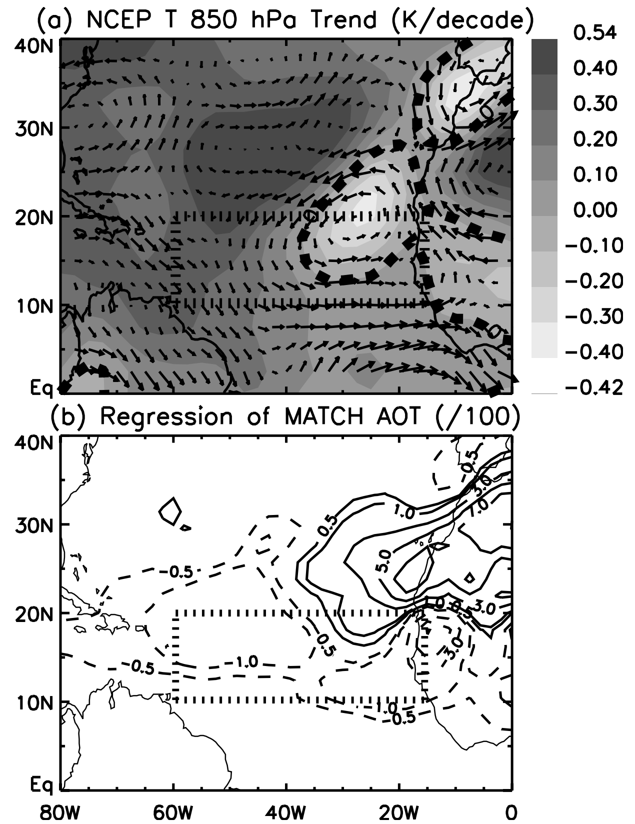

Figure 3. (a) August–September NCEP temperature trends (K/decade) at 850 hPa for the period 1979–2005. Also plotted are the NCEP winds at 700 hPa regressed on the PC associated with the temperature trends. (b) Regression of the MATCH dust AOT on the PC associated with the temperature trends. The numbers of the regression should be multiplied by 0.01 in order to get the real value of AOT per unit increase of the PC. The contour levels are ±0.5, ±1, ±3, ±5, and ±8. The contours of positive values are in solid lines, and the contours of negative values are in dashed lines. The dotted lines illustrate the tropical cyclone main development region.

[9] The trends in the model August-September dust AOT for the period 1979–2005 are plotted in Figure 1b. The shaded area covers the dust AOT trends that are non-zero at the 99% confidence level. Near the coast of West Africa, the MATCH model shows a significant negative trend of dust AOT from 8–20°N and a significant positive trend from 20°–30°N. The negative trend extends across the tropical North Atlantic to longitudes near 70°W.

[10] The corresponding PC time series for the model dust trends are shown in Figure 2a together with the AVHRR dust index averaged over the MDR. AVHRR also detects a negative trend in the dust amount over the MDR. The correlation between the MATCH and AVHRR time series is 0.87 for 1979–2005 (at 99% t-test confidence level, change in degree of freedom due to filtering has been considered).

[11] *Wong et al.* [2006] found that variations in summertime dust transport are associated with temperature anomalies near 850 hPa. By thermal wind relation, these temperature variations are related to variations in the circulation at 700 hPa, which has previously been identified as responsible for advecting Saharan dust off the coast of West Africa [*Carlson and Prospero*, 1972; *Jones et al.*, 2004; *Karyampudi and Carlson*, 1988; *Kaufman et al.*, 2005]. Therefore, we now investigate whether long-term temperature variation in the lower troposphere might be driving the decreasing dust trends in the MDR.

[12] Temperature trends (1979–2005) at 850 hPa are derived from NCEP reanalysis data, which is used to drive the MATCH model. The PC time series for the model August-September temperature trends are shown in Figure 2b, and the corresponding spatial patterns are shown in Figure 3a. The spatial pattern of the temperature trends at 850 hPa is a dipole, with positive trends in the subtropical central Atlantic around 30°–60°W and 20°–35°N, and negative trends over the eastern Atlantic around 20°–40°W and 15°–25°N.

[13] Also shown in Figure 2b is the North Atlantic SST time series. The 850-hPa temperature PC shows a very similar variation to the SST, with a correlation of 0.97 (99% confidence level) for 1979–2005. This high correlation indicates that the 850-hPa temperature varies coherently with the North Atlantic SST. Figure 4 shows the corresponding spatial pattern of the SST trend in August-September for 1979–2005. The SST warming trends are basin-wide, while the temperature trends at 850 hPa exhibit a dipole pattern (Figure 3a). It is not clear what mechanism causes this difference in spatial patterns between these two parameters. Further investigations are necessary to see if the altered transport direction of the warm SAL and the dust, which absorbs shortwave radiation, may play a role in modulating the temperature trends at 850 hPa.

[14] We have independently applied the rotated PCA to obtain the spatial patterns for the dust AOT trends (Figure 1) and the lower tropospheric temperature trends (Figure 3a) for the period 1979–2005. If the temperature change is responsible for the change in Saharan dust transport, we would expect that the linear regression of the dust AOT time series at every grid on the temperature PC time series should reproduce the AOT trend patterns shown in Figure 1b. This regression is shown in Figure 3b. Again, we see dust AOT generally decreasing in the MDR over the Tropical Atlantic. In the MATCH model, the dust amount is increasing over the North Atlantic northward of 20°N.

[15] To illustrate how the dipole temperature trends can influence dust transport, we plot in Figure 3a the regression of the time series of NCEP winds at each grid point at 700 hPa on the corresponding 850-hPa temperature PC time series from Figure 2b. The wind anomalies can be approximately related to the temperature trends at 850 hPa through the thermal wind balance. The cyclonic anomaly, centered at 25°W and 20°N, near the coast of West Africa would tend to reduce the advection of Saharan dust into the tropical North Atlantic between 10°–20°N (the MDR).

4. Conclusions and Discussion

[16] By using model simulations, we show that the warming trend in North Atlantic SST since 1979 is associated with a strengthening cyclonic anomaly at 700 hPa in the eastern Atlantic Ocean between 15°–25°N. This circulation anomaly suggests a northward shift of the African easterly jet, resulting in weakening easterlies at latitudes

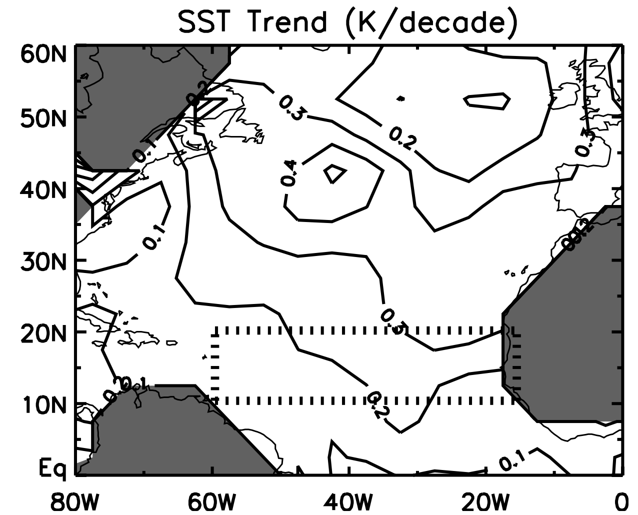

Figure 4. Linear trend in Kaplan North Atlantic SST (K/decade) in August-September for 1979–2005. The contour interval is 0.1, and the shaded area indicates the area with missing data.

between 10°–20°N that reduces dust being blown from Africa into the TC main development region. Since dust at these latitudes are correlated with Atlantic TC activity and associated with the warm and dry Saharan Air Layer, which has been shown to suppress the development of tropical cyclones [*Dunion and Velden*, 2004; *Evan et al.*, 2006a], it is possible that the warmer SSTs both directly influence hurricane intensity by increasing the potential maximum wind speed [*Emanuel*, 2005] and indirectly by altering the transport pathway of the dust-laden Saharan Air Layer.

[17] Since the variation in SST shown in this study is basin-wide, it is more likely that the change in SST affects the dust transport. If it were the trend in dust transport affecting the SST, one would have expected strong SST trend only in the dusty regions rather than the whole North Atlantic basin. Regardless of the reason behind this warming trend, our results demonstrate that rising SSTs are associated with an altered transport of Saharan dust over the North Atlantic Ocean. One intriguing possibility that we leave for future work is that, as the changing SSTs drive changes in the dust distribution, a feedback mechanism may exist if the changing dust in turn influences SST [*Evan et al.*, 2008; *Lau and Kim*, 2007]. A better understanding of such a system may be crucial for a complete understanding of how climate change will affect the intensity of tropical cyclones in the future.

[18] The change in dust distribution over the North Atlantic is also strongly correlated to lower tropospheric (850-hPa) temperature trends over the African continent. Since the temperature over land is highly controlled by the land-surface model being used, there may be discrepancies and uncertainties among different models as to where the positive dust AOT trend is exactly located. Further investigation is necessary to study Saharan dust AOT trends outside the MDR.

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